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R. Bamford, D. Moore, G. Mon and
B. Wada
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

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Jet Propulsion Laboratory
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ABSTRACT

The field of Adaptive Structures has expanded dramatically during the past few years. One definition of Adaptive Structures is a system whose geometric and physical structural characteristics can be beneficially modified to meet mission requirements either through remote commands or automatically in response to internal or external stimulations. The applications under study include Civil, Mechanical, and Aerospace systems. Overview of Adaptive Structures are in References [1,2]. For space, Adaptive Structures promise to (1) improve the reliability of deploy ment/assembly, (2) ease the implementation of ground test validation, (3) facilitate meeting precise structural requirements, and (4) allow redundancy in the mechanical systems. The efforts at the Jet Propulsion Laboratory to enable future space missions are in Reference [3]. Recently the Third International Conference on Adaptive Structures was held in San Diego [4].

In ninny applications of Adaptive Structures, the actuator, sensor and control functions are integrated directly into the structure itself. Often the capabilities are limited by the actuator. For static adjustments in currently planned space structures, a long stroke capability -- 15,000 μm (0.59 inch) -- with submicron resolution is required. The desire is for the actuator to maintain the changed position without the continuous application of electrical power. For dynamic applications, a dynamic stroke of 50 microns with submicron resolution with a large dynamic bandwidth is required. Although the load requirement when operational in space is generally small, the actuator must survive the loads induced in the ground test and launch environments. The direct use of ceramic piezoelectric actuators meets many of the requirements except for the long stroke, load carrying capacity, and capability to maintain the final position without power. Inch worm actuators are commercially available. but do not meet all the desired static and dynamic features in one actuator. The objective of the development of the "Mighty Worm" was to develop such an actuator. The adjective "Mighty" refers to the capability of the active member to carry large loads during the launch phase. The load path bypasses the piezoelectric actuator in the. launch mode.

The development of the actuator resulted in the first hardware about three years ago. Only recently was the testing of the actuators completed. The next generation inch worm actuator is currently being designed.

INTRODUCTION

The Mighty Worm actuator consists of a piezoelectric transducer, its housing, and two clamping devices, Figure 1. The transducer itself consists of several layers of piezoelectric ceramic wafers stacked upon a rigid baseplate. Upon respective application and removal of voltage, the ceramic stack expands and contracts relative to its base. The clamping devices act synchronously, one locking and releasing the baseplate while the other releases and locks the stack. Proper timing of stack voltage application and clamping action, Figure 2, enables device ("inchworm-like") motion, A single cycle sequence is (1) clamp the base; (2) apply stack voltage; (3) clamp the stack; (4) unclamp the. base: (5) remove stack voltage; (6) unclamp the stack. The timing of the clamping action is controlled by two elliptically-contoured cams mounted 90' out of phase on a motor-driven shaft: these cams flex lever-like clamps that alternately brake and release the base and stack of the transducer. The application of voltage is controlled by a relay whose OPEN-or-CLOSED state is governed by a notched wheel rotating (on the same shaft as the cams) between an LED and a photocell. Dual circuits allow forward and reverse motion, Figure 3.

The piezo-electric stack that is the heart of Mighty Worm is 68 mm long and extends a nominal 40 μm (1.6 mil) upon application of 1000 volts. The digits] dial gauge with which we measured stack expansion and Mighty Worm travel allowed a minimum reading of 1.27 μm (0.050 mil), permitting accurate positioning resolution to perhaps half that value, $\approx$ 0.6 μm ($\approx$ 0.025 mil).

It is required that a positioner/actuator for spacecraft adaptive. structures be capable of achieving both large-scale motion and precise positioning. In operation Mighty Worm pushes or pulls a load to within one stack expansion of the desired load position. This is the "long stroke" phase of Mighty Worm operation. Then, a final

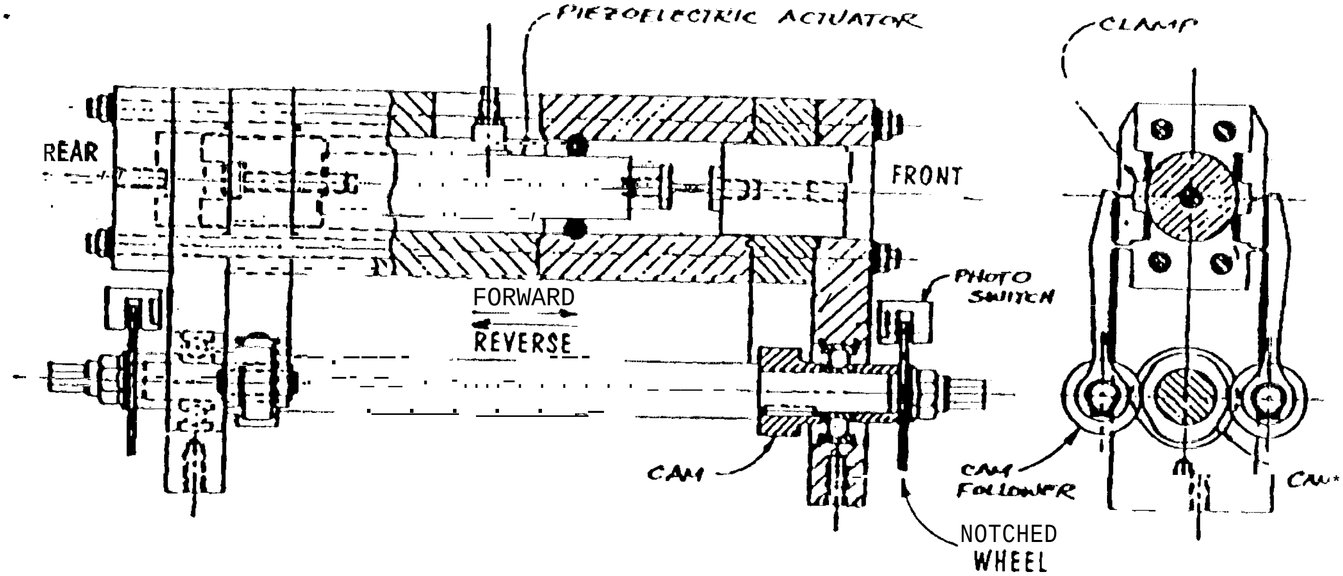

Fig. 1. Mighty Worm Actuator

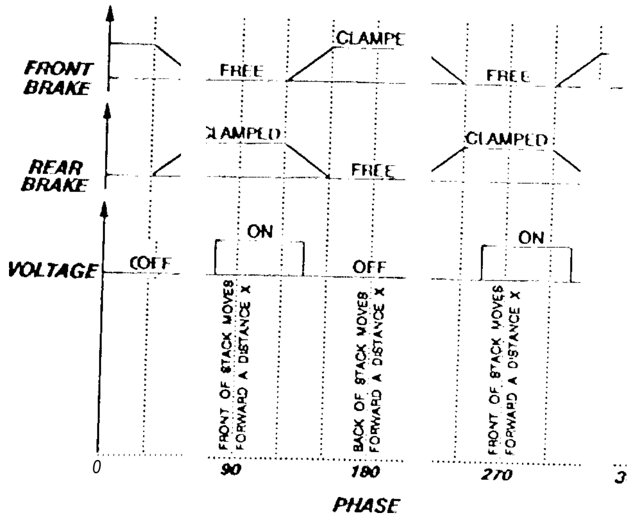

Fig. 2, Mighty Worm Timing Relationship

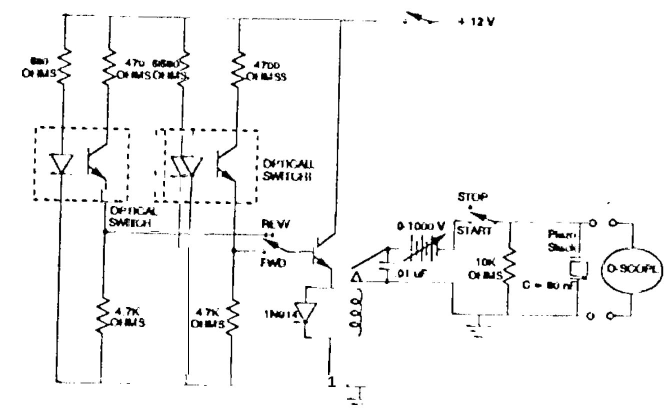

Fig. 3. Mighty Worm Circuit

cycle with application of an appropriate fraction of a kilovolt precisely positions the load. However, continuous power application is necessary to maintain position of the load. Had an electrostrictive actuator been used, no additional power would have been required.

Two types of Mighty Worm performance were characterized -- (1) long-stroke motion, and (2) incremental positioning -- at loads of O lb (NO LOAD), 25 lb, 50 lb, 75 lb, and 100 lb. The 100 lb maximum load limit is imposed by the fact that a 100 lb preload, designed into Mighty Worm, maintains the stack in perpetual compression. Long-stroke motion involves successive translations of all Mighty Worm moving elements; incremental positioning involves in-place stack expansion only.

INCREMENTAL POSITIONING

Incremental positioning data were obtained by loading the Mighty Worm and then incrementally applying (or removing) voltage. Mighty Worm does not move -- only the PZT stack extends or contracts. Note that the Mighty Worm can bc front- or rear-loaded (i. e., either the stack or the base can be loaded), so as to permit motion of the load upon either stack expansion or contraction. There are four cases:

Case	Moving element	Element moves by
1	Front	contraction
2	Front	expansion
3	Rear	expansion
4	Rear	contraction

"Front" arid "rear" are defined in Figure 1. Motion is relative to the non-moving element toward the moving element.

Cases 1 and 4 (motion upon contraction), and Cases 2 and 3 (motion upon extension), appear to be identical cases but for the direction and point of application on the PZT of the load. However, the data did not reflect this seemingly obvious expectation. Figures 4 and 5, depicting Cases 2 and 3, respectively, display similar behavioral characteristics but with important differences.

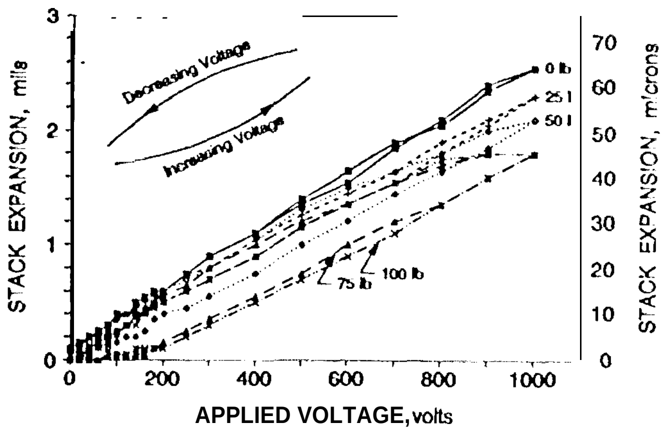

Fig. 4. Mighty Worm Incremental Positioning. Increasing and Decreasing Volts, Case 2

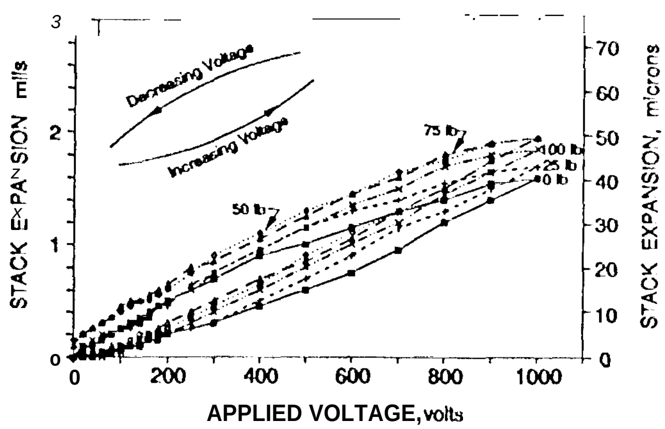

Fig. 5. Mighty Worm Incremental Positioning. Increasing and Decreasing Volts, Case 3

in both cases, extension and contraction are not quite linear, but rather more or less parabolic, functions of applied voltage. There is also a quite noticeable hysteresis and a less obvious threshold voltage -- probably a manifestation of device friction -- that must be exceeded before stack expansion achieves its maximum increment for equal applied voltage increments.

Note that with Case 2 loading, resolution decreases with increasing load, whereas with Case 3 loading, Fig. 5, resolution slightly increases with increasing load. At 1000 volts, the Case 2 and Case 3 NO LOAD extensions differ by as much as 25 μm (1 roil). The 100 lb load lines for both cases are about the same,

Figure 6 presents incremental Positioning data for Case 4 loading. In this case, upon removal of increments of applied voltage, the stack contracted, pulling the load. 'l'he data mirror imaged those for Case 3 loading (Fig. 5).

The message here is that stack expansion is approximately 40 μm (1.6 roil) per kV. We have demonstrated an ability to position accurately to within 0.62S μm (0.02.5 mil), which corresponds to a voltage increment of approximately 16 volts.

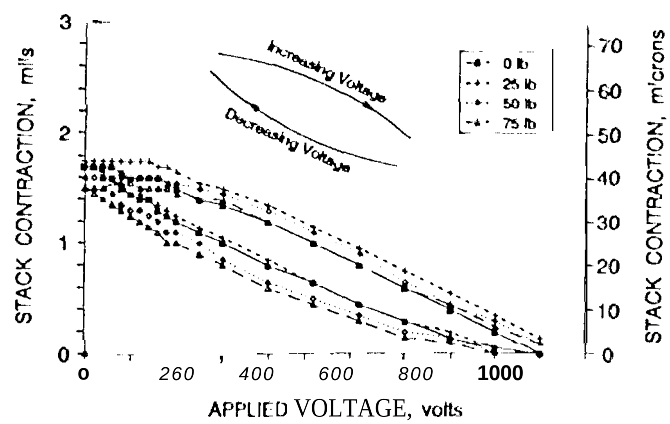

Fig. 6. Mighty Worm Incremental Positioning. Increasing and Decreasing Volts, Case 4

LONG-STROKE PERFORMANCE

Creepage

We defined creepage as the Mighty Worm travel per cycle with only the shaft drive motor operating -- i.e., no applied voltage, no applied load. For motor speeds between 60 rpm and 280 rpm, the creepage was never greater than 0.035 roil/rev (O. 88 pm/rev). This value is at least an order of magnitude below the range of measured operational resolutions and is less than the minimum resolution, 1.27 μm, of the dial gauge; hence, creepage effects were ignored in all characterization data.

Creepage may result from unbalanced mechanical forces in the Mighty Worm design, e.g., slight twisting of one bearing surface relative to another, unaligned or off-axis forces, etc. Every effort will be made in future design cycles to eliminate these effects.

No Load

NO LOAD data gathered under full dynamic operation of Mighty Worm is presented in Figure 7. These data show that the $\mu m/rev$ resolution increases with applied voltage, more in a parabolic than in a linear fashion, and is independent of shaft rpm. The maximum measured NO LOAD resolution was about 90 $\mu m/rev$ (3.5 mil/rev) at 1 kV.

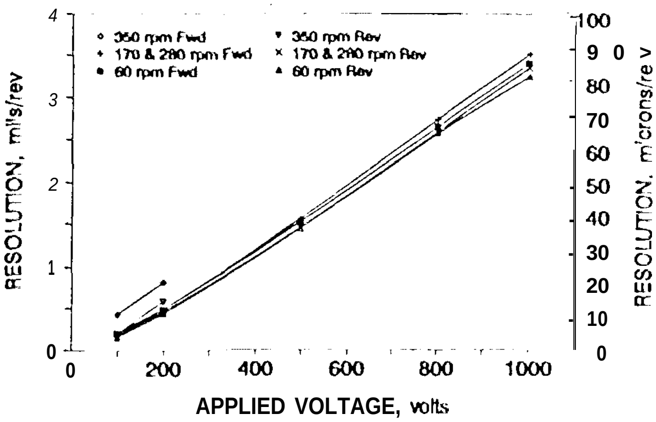

Fig. 7. Mityworm Long-Stroke, No-Load Data

Load

Dynamic load data were gathered in the Case 4 configuration at 60 r-pm, Figure 8, and at 280 r-pm, Figure 9, for applied loads of O lbs, 25 lbs, 50 lbs, 75 lbs, and 100 lbs. his data clearly shows that the threshold voltage phenomenon noted earlier in incremental positioning measurements applies as well to long-stroke resolution -- namely, at larger loads, a greater applied voltage is required in order to initiate movement. In fact, 100 lb loading, Figure 8, requires over 800 volts to initiate forward motion; at lower applied voltages, there is either no motion or the Mighty Worm moves in the reverse direction. Furthermore, long-stroke resolution decreases with increasing load. The resolution at 280 rpm is a bit larger than at 60 rpm.

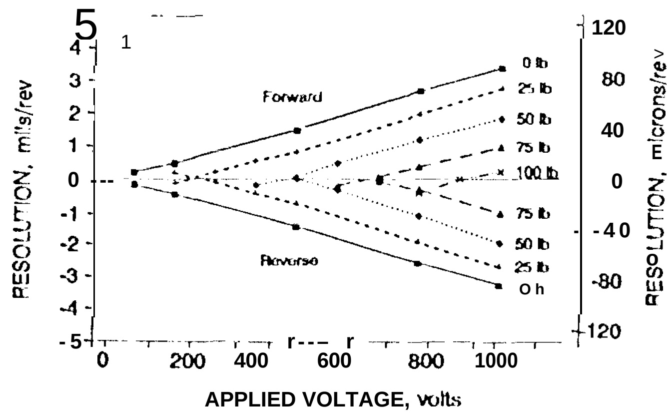

Fig. 8. Mighty Worm Long-Stroke Load Resolution. Forward and Reverse Travel, 60 rpm

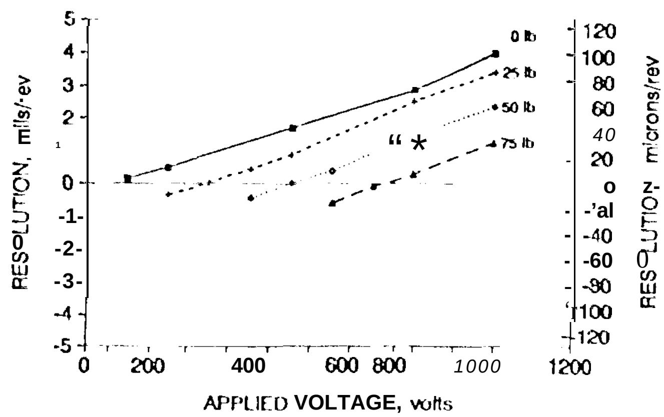

Fig. 9. Mighty Worm Long-Stroke Load Resolution. Forward Travel, 280 rpm

DEVICE PHYSICS

Dynamic Loading Considerations

Figure 10 is a schematic diagram representing a single 'firing" of Mighty Worm. In each %-revolution of the shaft motor, Mighty **Worm undergoes one extension-relaxation cycle.** Electrical energy $E = \frac{1}{2} \cdot C \cdot V^2$ is supplied; the net result is a translation of Mighty Worm, and hence the. movement of the load F, a distance x. The net work done is **W = F*x.** Then, ignoring dissipative forces,

$$W = E \implies \frac{1}{2} \cdot C \cdot V^2 = F \cdot x \qquad (1)$$

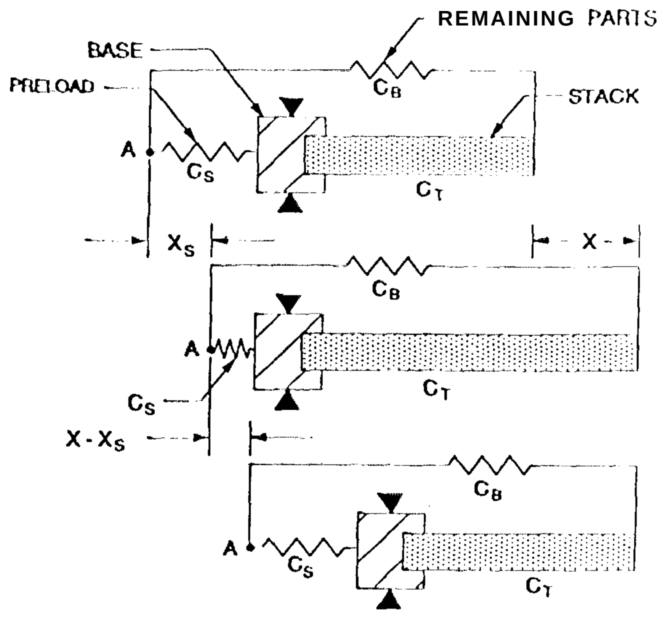

Fig. 10 Schematic of Mighty Worm Translation

This gives $x = C \bullet V^2/(2 \bullet F)$ for the distance translated per ½-revolution. **What** we term the resolution per revolution **(res/rev)** is

$$\cap = 2 \bullet x = C \bullet V^2/F \tag{2}$$

where

C = Mighty Worm nominal capacitance = 80 nF
V = applied voltage
F = **applied** load

The resolution per revolution is directly proportional to the **square of the voltage and inversely proportional to the applied load, trends** that have been observed in the data. For a typical Mighty Worm case -- F = 100 lb and V = 1000 volts -- $\cap$ = 280 μm (7.1 **mil).** For this particular case we have observed $\cap \approx$ 6.25 μm (0.25 roil) -- considerably less than **Eqn.** (2) predicts.

An accounting of energy sheds some light on what is occuring. The work done **in** moving a 100 lb load a distance 0.25 **mil** (6.25 **μm)** is 2.83 rnJ. The various Mighty Worm stiffness element energies **add up to** $\frac{1}{2} \bullet c_T \bullet x^2 + \frac{1}{2} \bullet c_S \bullet x_S^2 + \frac{1}{2} \bullet c_B \bullet (x - x_S)^2 \approx$ 0.3 mJ, where **we have used (Fig. 10)**

$$x_S = \frac{c_B}{c_B + c_S} \bullet x \tag{3}$$

and

c_T = Mighty Worm stack stiffness, 79 lb/mil
c_S = preload spring stiffness, 4 lb/mil
c_B = remaining parts stiffness, 34.5 lb/mil

So the energy required to translate 0.25 mil is about 3.13 mJ.

The supplied energy/cycle is $\frac{1}{2} \bullet C \bullet V^2$ = 40 mJ. This, however, is probably not correct, for the manufacturer of the piezo device says that piezoelectric stack capacitance will increase by as much as a factor of 2 with both increasing stack extension and increasing load. For example, Figure 11 shows the Mighty Worm energy dissipated across the 10 KΩ bleed resistor for a load of 100 lb and an applied voltage of 1000 volts. The dissipated energy is about 75 mJ, approximately twice that computed using the nominal value of Mighty Worm stack capacitance.

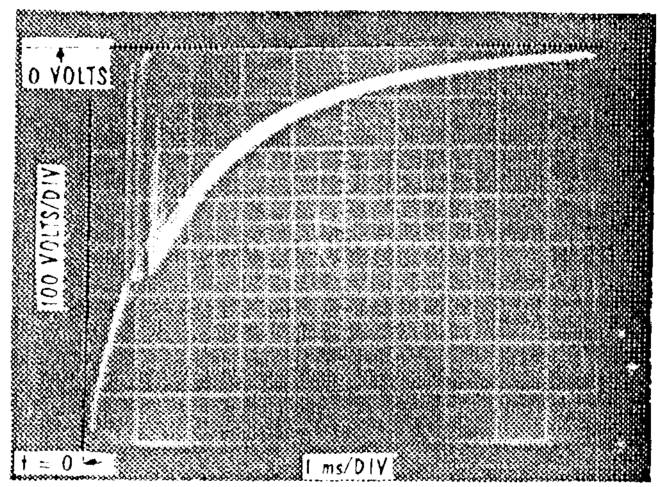

Fig. 11 Mighty Worm Dissipation Across 10 KΩ Bleed Resistor. 1000 volts 100 lb Load

So 37 mJ out out of 40 mJ, or perhaps as much as 75 mJ out of 78 mJ, -- most of the energy supplied -- is not consumed mechanically. Much of the supplied energy was observed to be dischaged across the 10 KΩ bleed resistor. Some energy was thought to be dissipated as heat generated in Mighty Worm extension-relaxation cycles, but a thermocouple attached close to the Mighty Worm stack elements did not register a temperature increase during Mighty Worm operation.

Static Loading Considerations

Assuming that the application of the same voltage V always induces the same extension force within the ceramic. stack, one can derive

$$x \cdot x_o \cdot \frac{c_T \bullet \{c_S + c_B\}}{c_T \bullet c_S + c_T \bullet c_B + c_S \bullet c_B} = 0.96 \bullet x_o \quad (4)$$

where x_o is the free extension of the Mighty Worm stack element, about 1.6 roils. This result changes by less than 1 % if the remaining parts are rigid, permitting the use of a somewhat simpler model to study Mighty Worm performance.

The result, Eqn. (4), is independent of static, i.e., constant, loading. Stack mechanical stiffness is 79 lb/mil, so 100 lb will compress the stack about 1.25 roil. Application of 1000 volts nominally extends the stack about 1.6 mil. But the 100 lb / 1000 volt incremental positioning data do not give a resolution of 1.6- 1.25 = 0.35 roil, but rather a resolution of about 1.6 roil. Thus for a 100 lb load, there is no guarantee that any fine motion capability exists. Generally, as we go to higher loads, we lose capability to move in one direction, see Figure 8.

DISCUSSION

One. hazard of cyclic flexing of the Mighty Worm braking mechanisms is the potential fatigue failure of the clamps. We in fact experienced two such failures: one at 313,000 cycles and another after 6500 additional cycle-s. Both failures were repaired and testing continued. We suggest the use of more fatigue resistant materials and improved fatigue design for the clamping mechanisms -- i.e., less strain range during clamp flexing.

We believe that one contribution to discrepant incremental positioning data is the fatigue failures -- some of that data were acquired before the fatigue failure and some of it after the clamp was repaired (i. e., welded). This repaired part may not have had the same stiffness, or the same registry with the cams, as it had prior to the. fatigue failures Another factor contributing to data uncertainties is the unknown effect of system friction on Mighty Worm performance, particularly incremental positioning.

Due to hysteresis and non-linearities, open-loop positioning of Mighty Worm cannot be accomplished, i.e., applying a predetermined voltage may not result in the desired stack extension. To achieve precise positioning, external position sensing with feedback (i. e., closed-loop control) is necessary, or a piezo device with an internal position sensor could be used.

Unquestionably, this Mighty Worm design can be improved. Nevertheless, this design was more than adequate to glean some understanding of the. physics of Mighty Worm and, most importantly, to demonstrate "proof of concept", i.e., the capability of Mighty Worm to move and accurately position a load.

A Final Note

During Mighty Worm brake testing, we noticed that Mighty Worm responded to an earthquake, i.e., the vibration of the load, effectively a pendulum, translated into voltage variations observed on an oscilloscope. This suggests that Mighty Worm, suitably redesigned, may have application as a seismic sensor.

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